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Statement of
Dr. Piers Sellers
Deputy Director, Sciences and Exploration Directorate
NASA Goddard Space Flight Center
Before the
Committee on Commerce, Science, & Transportation
Subcommittee on Science and Space
United States Senate

Chairman Nelson and Members of Congress from the state of Florida, it is my pleasure to appear before you today to discuss the state of science on climate change, with particular reference to global warming, sea level rise and the likelihood of increases in the intensity of extreme weather events. I would like to share with you the science community's current understanding of why the climate is changing, how it is changing and what some of these predicted changes mean for your coastal areas. We hope that this information will be directly useful to policy makers and citizens in setting policies and for planning necessary adaptation and mitigation efforts.

Earth science has made some amazing advances over the last three decades, principally thanks to the data provided by a constellation of Earth-observing satellites. The view from orbit allows us to observe the whole world, many times per day, using a very wide spectrum of techniques and, most importantly, using a small set of well-understood instruments. NASA has been at the forefront of this effort, with significant contributions also provided by NOAA, USGS and our international partners. These observations help us understand our planet better, and thus improve our ability to project likely future climate states, and also yield powerful societal benefits in terms of improved weather prediction, agricultural applications and water resources management, to name a few.

Senator Nelson and I have both had the privilege of seeing the world from space. Spaceflight allows one to stand back, or float, and literally take in the "big picture". My take-home impression, and when I say home, I mean here – Earth – is that we inhabit a very beautiful but delicate planet. And the dynamic engine of planet Earth is the climate system that allows all life here to prosper and grow, including us humans.

The global climate is defined as the long-term statistical behavior of the atmosphere, ocean, cryospheric and associated bio-geochemical cycles. Broadly speaking, climate is what you expect in a given year, based on long-term records and some understanding of the underlying physics, while weather, which varies from year to year, is what you actually get. Sophisticated computer models of the Earth system use satellite and other data to provide better weather forecasts. Closely related models, based on the same physical principles, are used to study the climate.

The world's climate has been observed to change over many time-scales as a result of many potential causes. Over the last 150 years[1], the evidence from multiple archives consistently shows that surface temperatures have warmed on average by about 0.85ºC (1.6ºF)[2], but with higher increases over land and in the Northern high-latitudes, see figure 1. A wide range of studies indicate that most of this increase in temperature, and associated increases in atmospheric water vapor pressure, ocean heat content and the decreases in Arctic ice extent and mountain glaciers since 1950, at least, are very likely due to human activities[3].

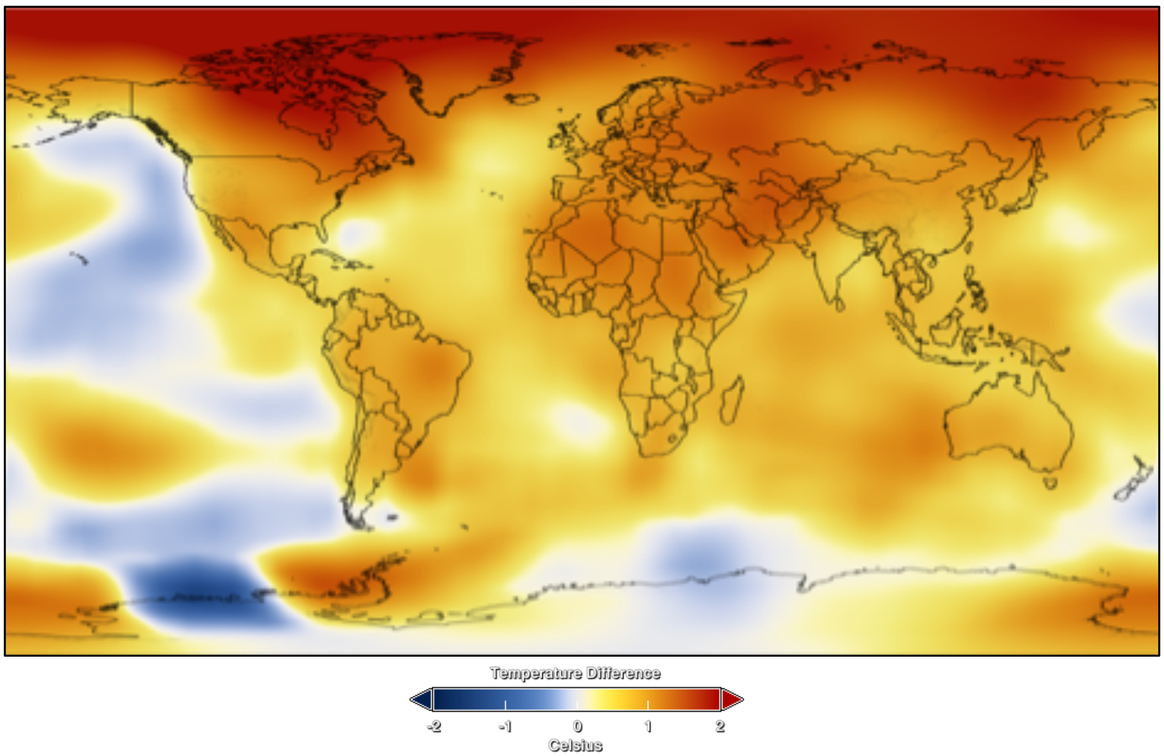

Figure 1. Color-coded map of global temperature anomalies averaged from 2008 to 2012. Reprinted from *Five Year Global Temperature Anomalies* by L.Perkins, 2013, Retrieved from svs.gsfc.nasa.gov/vis/a000000/a004100/a004135/ and based on data from data.giss.nasa.gov/gistemp/.

The best estimate is that human activities have contributed close to 100% of the observed warming over the last 60 years or so.[4] There have been some significant natural variations (warming and cooling) in global temperature over this same period due to oscillations in the oceans and other factors, but on average these have roughly cancelled each other out. Greenhouse gases from fossil fuel burning act as a radiation-trapping blanket in the Earth's lower atmosphere and are very likely the main cause of the global

[1] IPCC 5 Working Group 1 figure 10.5
[2] IPCC 5 Working Group 1
[3] IPCC ARS, Working Group 1 Summary for Policy Makers
[4] IPCC 5 Working Group 1

warming post 1950. The evidence suggests that the most important human drivers of change are the large increases in well-mixed greenhouse gases (particularly carbon dioxide, methane, and chlorofluorocarbons) and impacts of atmospheric aerosols (sulfates, black carbon, nitrates). Smaller effects are associated with ozone changes at the surface and in the stratosphere along with land use changes (deforestation, irrigation). Natural drivers of change such as solar activity and volcanic eruptions have detectable fingerprints of change in the observations, but these changes are not large enough to appreciably add to the long-term warming.

The global climate, in simplified terms, is a response to the overall energy flow between solar forcing (heat), ocean and atmospheric heat transport and storage of this energy and the return of the energy back to space through infra-red emission. NASA's Earth Science program has a strong emphasis on understanding these changes in the global energy and water cycles using computer models and the current constellation of 17 satellites, with more planned. Given the continued increase in greenhouse gases that slow the loss of infrared energy to space, the planet is predicted to be out of energy balance – that is, more energy is coming into the system than is leaving. About 90% of this extra energy has been used to warm the oceans, with about 7% to melt ice and only 3% to warm the atmosphere. The increase in ocean heat content over the last few decades is shown in figure 2. This resulting net flow of heat into the climate system is driving many of the changes that we are here to talk about today.

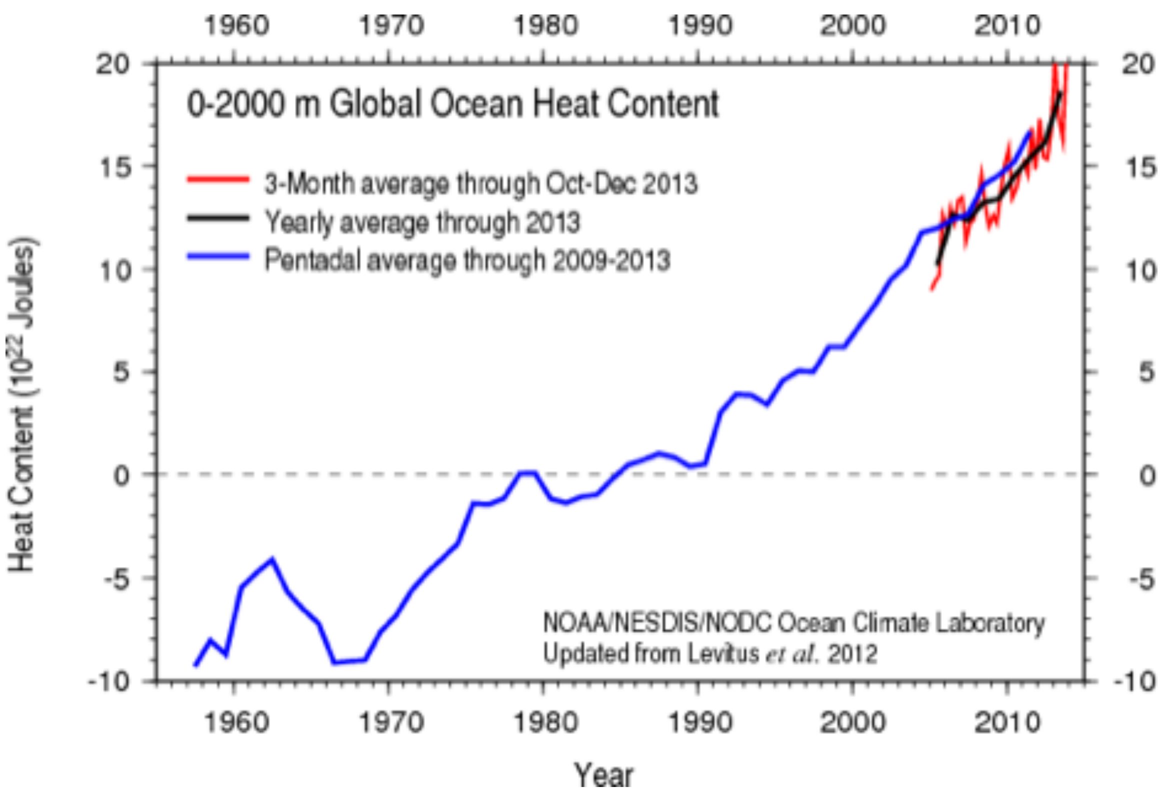

Figure 2. Global Ocean Heat Content. Reprinted from *Global Ocean Heat and Salt Content* by S. Levitus, 2012, Retrieved from www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/. Based on Levitus, S., J. I. Antonov, T. P. Boyer, K. Baranova, H. E. Garcia, R. A. Locarnini, A. V. Mishonov, J. R. Reagan, D. Seidov, E. S. Yarosh, and M. M. Zweng

(2012), World Ocean Heat Content and thermosteric sea level change (0-2000 m), 1955–2010, *Geophys. Res. Lett., 39,* L10603, doi:10.1029/2012GL051106, 2012.

Impacts of current climate change can be seen in multiple independent datasets that come from in situ physical measurements and remote monitoring by satellite. Figure 3 shows the decline in Arctic sea ice as measured by satellite sensors over the last three decades – it can be seen that the minimum Arctic sea ice extent has significantly decreased over that time.

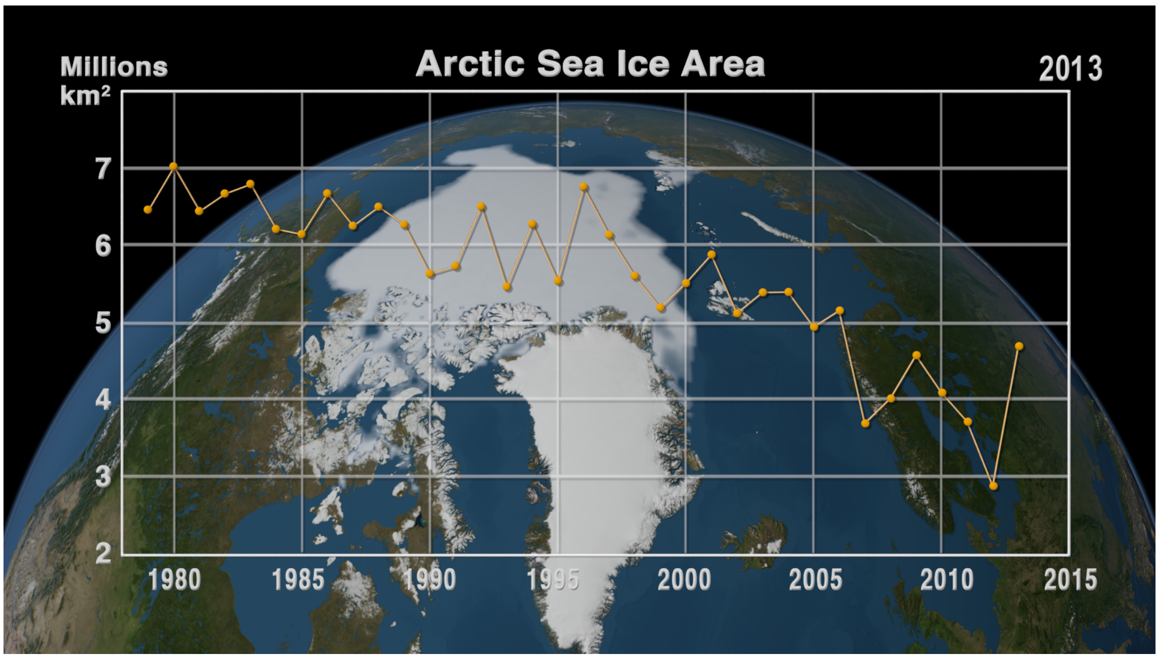

Figure 3. Annual arctic sea ice minimum from 1979 to 2013 based on satellite-based passive microwave data. Reprinted from *Annual Arctic Sea Ice Minimum 1979-2013 with Area Graph* by C.Starr, 2013, Retrieved from svs.gsfc.nasa.gov/vis/a000000/a004100/a004131/

Sea level can be very accurately measured by satellites and since 1993 NASA and its partners, principally NOAA and the French space agency CNES, have been monitoring sea level continuously from space using satellite altimetry missions including Topex/Poseidon, Jason 1 and Jason 2 over this time period. Future missions include Jason-3 (launching in 2015) and the Surface Water Ocean Topography (SWOT) mission. Tide gauges provide independent assessments of altimeter data and provide region-specific information. These in situ data inform local projections that can differ from the global picture because of local ground movements and regional ocean currents. Figure 4 shows the measured rise in sea level from these satellite data sources.

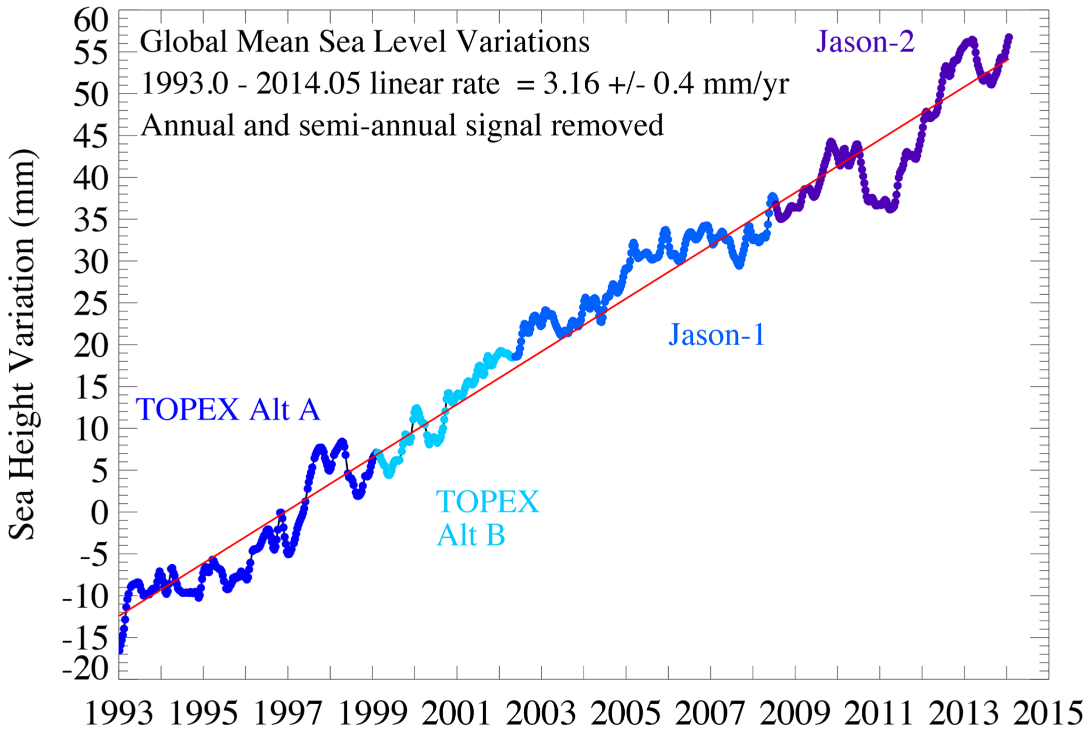

Figure 4. Global mean sea level rise based on data from satellite altimetry.

It can be seen that global sea level has increased by over 3 mm/year over the last 20 years. Projections of the expected increase in sea level rise over the 21st century have also been raised as we have learned more about ice sheets, groundwater changes and ocean heating, see figure 5.

The 2007 Intergovernmental Panel on Climate Change (IPCC) report was unable to give a range for the contribution of ice sheet melt to sea level rise (but suggested that other terms would lead to a maximum of 59cm by 2100). In the 2014 IPCC report, there are still large uncertainties in the maximum scenarios, but the ‘likely’ range has been expanded to up to 98cm[5]. Some of NASA’s ongoing research programs are directly aimed at reducing this uncertainty.

[5] IPCC ARS Working Group 1

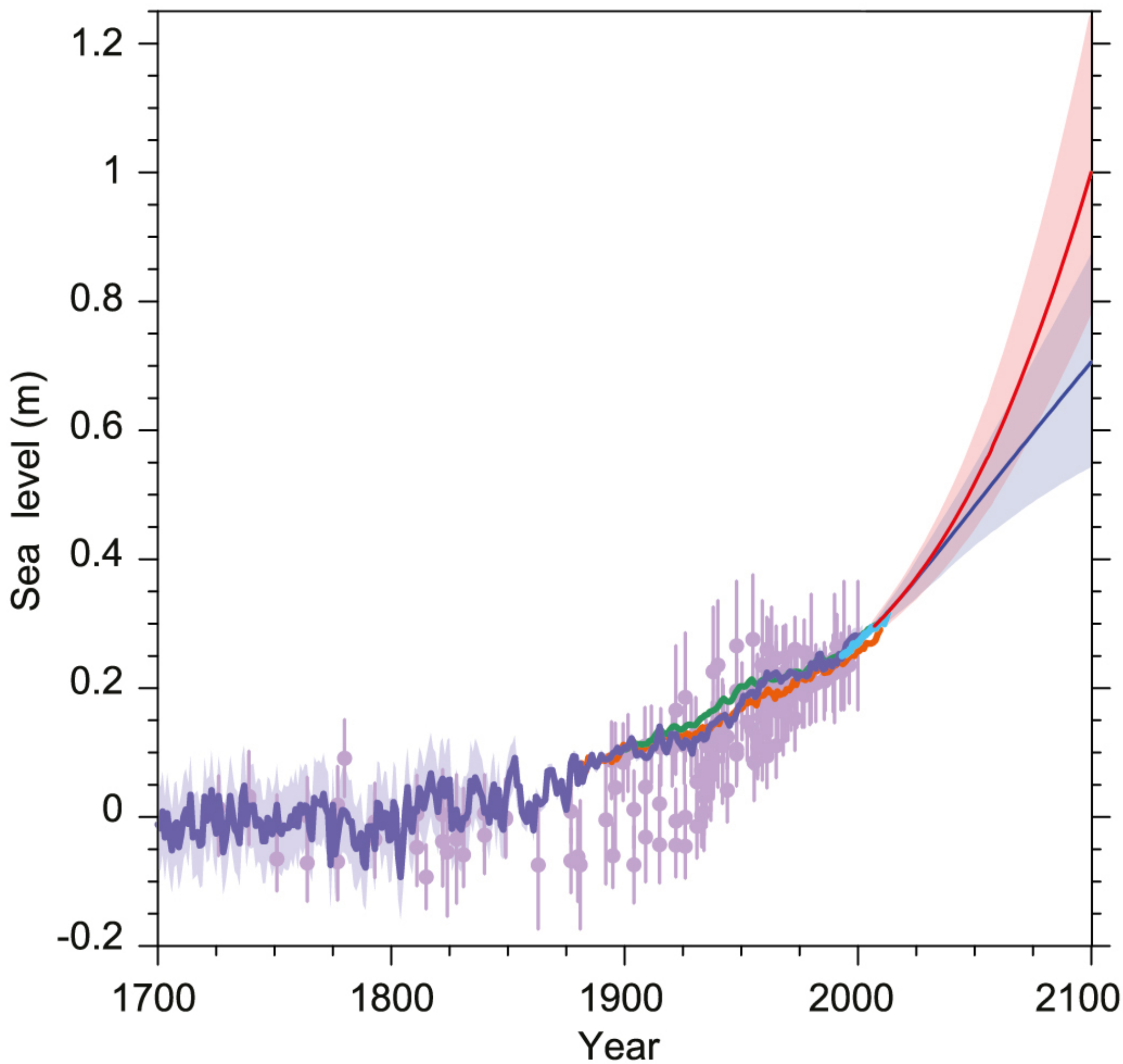

Figure 5. Compilation of paleo sea level data, tide gauge data, altimeter data, and central estimates and likely ranges for projections of global mean sea level rise for **RCP2.6 (blue)** and **RCP8.5 (red)** scenarios, all relative to pre-industrial values. From Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

The principal factors that affect global sea level are ocean temperature, ice volume, and tectonic activity. Over short, decadal and centennial, time scales, sea level is most influenced by temperature and ice volume changes. Currently, most of the change in global sea level is the result of increases in ocean heat content as the ocean expands very slightly as it warms. The melting of glaciers is estimated to have contributed about one third of the observed sea level rise shown in figure 4. As the global climate warms further, contributions from melting of the Greenland and Antarctic ice sheets will become more significant. Both ice sheets have lost ice at an increasing rate since the 1990’s. In particular, Gravity Recovery and Climate Experiment (GRACE) satellites that can measure small variations in the Earth's gravity field from space show that significant amounts of ice sheet and glacier melting are occurring in Greenland, Alaska and West Antarctica. Figure 6 shows the latest estimates of the annual decrease in the mass of the Earth's major ice sheets, derived using four independent data sources over the last few decades.

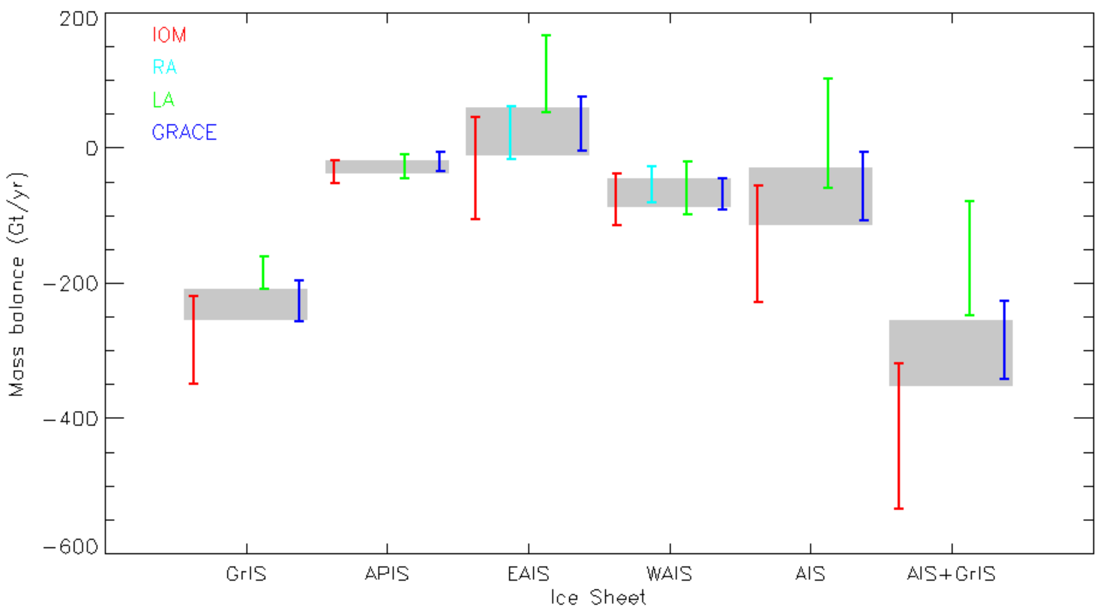

Figure 6. Intercomparisons of ice mass balance estimates using four independent geodetic techniques: Input-Output Method (IOM), red), Radar Altimetry (RA, cyan), Laser Altimetry (LA, green), and gravimetry (GRACE, blue). Four regional areas are considered: the Greenland Ice Sheet (GrIS), Antarctic Peninsula Ice Sheet (APIS), East Antarctic Ice Sheet (EAIS), West Antarctic Ice Sheet (WAIS), the combined Antarctic Ice Sheet (AIS), and the overall estimate for the AIS and GrIS. The grey areas constitute the reconciled estimates. From Shepherd, A., et al., *A Reconciled Estimate of Ice Sheet Mass Balance*, Science, 2012

With the development of satellite and airborne remote sensing capabilities, coupled with improved field measurements and modeling efforts, we are beginning to understand current changes and gain insights into what the future may hold for the Greenland and Antarctic ice sheets. Our satellite and airborne capabilities are providing observations of glacier flow rates, ice topography (which is indicative of the underlying processes that affect change), mass change, and depth and topography of the bedrock that lies beneath the ice. This last point is particularly important because the geometry of the bed, in conjunction with surface elevations, largely determines the extent to which glaciers will continue to accelerate or will slow down.

Current and planned investments in missions such as the Ice, Cloud and Land Elevation Satellite 2 (ICESat-2 -- measuring ice elevation change) and the Gravity Recovery and Climate Experiment (GRACE) follow-on measuring ice mass change) and airborne observations of ice topography and glacier bed geometries provide insights into the underlying mechanisms of ice sheet changes. Space geodesy, satellite and airborne radars all provide more information that helps to pin down details related to glacier motion and ice sheet changes. NASA also works with data from its international partners to examine the variations in flow rates of outlet glaciers, tracking the magnitude and character of their acceleration. The information gained from all of these projects is incorporated into ice sheet models designed to predict how ice sheets will contribute to sea level rise in the next one or two centuries. The modeling activity is an integrated effort jointly carried out by NASA, the National Science Foundation, and the Department of Energy (DOE). NSF also invests in basic observations and process studies that are either directly coordinated with or are complementary to NASA's activities, and DOE is building dynamical models of Greenland and Antarctica, where future sea level rise projections take advantage of observations provided by NASA and NSF.

Sustained observations of ocean elevation from satellites combined with tide gauges will provide continuous measurements of sea level rise. Current and planned observations of ice sheets and glaciers will provide necessary insights into the physical processes that govern their contributions to sea level rise. Ongoing and planned measurements of ocean characteristics will continue to inform our assessments of temperature and circulation characteristics, which affect the rate of expansion. Continued observations of the movement of water throughout the Earth will provide important insights into the characteristics of land-water storage. All of these data are critical inputs used to inform models and improve our understanding of the physics, carrying us closer to a more complete and robust sea level rise prediction.

The net flow of heat into the climate system that I referred to earlier is likely to affect the intensity and frequency of extreme weather events in many parts of the globe. Our ability to predict changes in the likelihood of these events is so far relatively limited but intensive research continues in this important area. The most recent report of the International Panel on Climate Change (IPCC 5) states that it is likely that the global ***frequency*** of tropical cyclones will either decrease or remain essentially unchanged owing to greenhouse warming. These findings speak directly to tropical cyclones, not other severe weather events. Projected decreases in tropical cyclone frequency appear to be related to a weakening of the tropical circulation associated with a decrease in the upward mass flux in regions of deep convection under global warming. However, there is lower confidence associated with these projections.

The predicted change in storm intensity is a different story- and one we can speak to with greater confidence. Calculations indicate that the mean maximum wind speed of tropical cyclones is likely to increase by +2 to +11% globally due to the projected twenty-first-century warming, although increases may not occur in all tropical regions. Two studies referred to in the latest IPCC report project near-term increases of North Atlantic hurricane intensity driven in large part by projected reductions in tropospheric aerosols. The frequency of the most intense Category 4 and 5 storms will more likely than not increase by a substantially larger percentage in some basins, including the North Atlantic. For the North Atlantic, an estimate of the time scale of observed emergence of projected changes in intense tropical cyclone frequency is longer than 60 years. This is because these are relatively rare events and getting a statistically significant sample takes time.

NASA's Hurricane and Severe Storm Sentinel (HS3) mission is delivering important information that will improve our ability to predict the track and intensity of hurricanes as well as provide information related to how hurricanes may intensify in a warming world. HS3 uses two Global Hawk unmanned aerial vehicles to fly around and over storms developing in the Atlantic. The Global Hawks are capable of extended missions, 24 hours or longer, and make multiple passes over the developing storms, tracking the wind and convective processes that lead to a storm's intensification or weakening. As sea levels rise, enhanced understanding of hurricanes and their potential intensities and tracks will become ever more important.

Rainfall rates associated with storms are likely to increase. The projected magnitude is on the order of +20% within 100 km of the tropical cyclone center. The increase in rainfall rates associated with tropical cyclones is a consistent feature of the numerical models projecting greenhouse warming as atmospheric moisture content in the tropics and tropical cyclone moisture convergence is projected to increase. This increase in rainfall may increase flooding potential along the tracks of land-falling storms. Resulting changes to water vapor pathways and the dynamical pattern of the troposphere may lead to increased coastal rainfall and drying continental interiors. NASA's Tropical Rainfall Measuring Mission (TRMM) and the recently launched Global Precipitation Mission (GPM) are providing detailed information to help better understand relationships between rainfall and tropical cyclone intensity, and how tropical cyclones and extreme weather events can affect the US and regions around the world.

There is low confidence in projected changes in tropical cyclone genesis location, storm tracks, duration, and areas of impact. Existing model projections do not show dramatic large-scale changes in these features. However, the vulnerability of coastal regions to storm-surge flooding is expected to increase with future sea-level rise and coastal development, although this vulnerability will also depend on future storm characteristics.

What does all of this mean for Florida? By the end of the century, the intensity of hurricanes, including rainfall near the centers of hurricanes, may increase. It is not currently possible to determine whether the number of hurricanes impacting Florida will change. But even if hurricane frequency and intensity do not change, rising sea levels and coastal development ***will likely increase the impact*** of hurricanes and other coastal storms on those coastal communities and infrastructure. It is important to remember that it is the combination of a steady increase in sea level combined with a projected increase in rare but extreme weather events which represents the greatest threat to Florida's coastal areas.

In closing, I emphasize that our ability to continuously observe changes in the global climate system, including ice sheets, sea level, and ocean characteristics, is critical to improving our understanding of the physical processes at work. All the data collected by NASA are made freely available to researchers and the public. Scientists in NASA and elsewhere in the US and internationally are studying changes in the Earth's system as a matter of high priority in order to provide you – the citizens and leaders of this country – with the best possible information with which to prepare for the future. These sustained measurements and the supporting scientific research are critically important to improving our understanding of this planet and will allow us to better predict the phenomena associated with global climate change.